Thermal response of the mantle following the formation of a "super-plate"

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[1] Evidence indicating that the mantle below Pangea was characterized by elevated temperatures supports the widely held view that a supercontinent insulates the underlying mantle. Implementing a 3D model of mantle convection featuring distinct oceanic and continental plates, we explore different effects of supercontinent formation on mantle evolution. We find that a halt in subduction along the margins of the site of the continental collision is sufficient to enable the formation of mantle plumes below a composite "super-plate" and that the addition of continental properties that contribute to insulation have little effect on sub-continental temperature. Our findings show that the mean temperature below a supercontinent surpasses that below the oceanic plates when the former is a perfect insulator but that continental thermal insulation plays only a minor role in the growth of sub-supercontinent mantle plumes. We suggest that the growth of a super-oceanic plate can equally encourage the appearance of underlying upwellings. **Citation:** Heron, P. J., and J. P. Lowman (2010), Thermal response of the mantle following the formation of a "super-plate," *Geophys. Res. Lett.*, *37*, L22302, doi:10.1029/2010GL045136.

1. Introduction

[2] The lack of participation of the thick continental lithosphere in global mantle circulation and a radioactively enriched continental crust suggest that continental plates act as buoyant thermal insulators [*Anderson*, 1982; *Lenardic et al.*, 2005; *Phillips and Bunge*, 2007; *Coltice et al.*, 2007]. In addition, it has been argued that supercontinent assembly results in subcontinental warming because the underlying mantle is isolated from the cooling associated with subduction [*Anderson*, 1994]. Indeed, seismic tomography [e.g., *Romanowicz*, 2008] and geoid highs [*Anderson*, 1982] over the current location of Africa indicate that the mantle below central Pangea's former location is warmer than the global average.

[3] Numerous mantle convection studies have shown that hot plumes appear below model continental plates caught between convergent plate boundaries [e.g., *Gurnis*, 1988; *Lowman and Gable*, 1999; *Zhong et al.*, 2007] or below buoyant rheologically defined rafts [e.g., *Zhong and Gurnis*, 1993; *Yoshida et al.*, 1999; *Honda et al.*, 2000]. Nevertheless, these studies do not clearly validate the notion that insulation following supercontinent assembly results in mantle heating on time scales relevant to the Earth's evolution. Rather, they demonstrate that plumes will preferentially form where downwellings are suppressed. Clarification of the role of continental thermal insulation on subcontinental mantle temperatures is important. If insulation plays a secondary role in the evolution of the deep mantle's thermal field then super-oceanic plates should also provide the conditions conducive to nurturing the growth of underlying plume clusters or superplumes.

[4] Modeling studies show that convection influenced by the presence of oceanic plates significantly differs from convection in which plate-like surface motion is absent [*Bunge and Richards*, 1996; *Monnereau and Quéré*, 2001]. However, many studies examining the effect of continents on mantle evolution omit the influence of oceanic plates. Large oceanic plates reduce heat flow [*Monnereau and Quéré*, 2001] and may themselves influence mantle thermal evolution in a manner similar to supercontinents. Here, we model the response of the mantle following the formation of a "super-plate". Systematic variation of the mechanical and thermal properties of the large plate (which is surrounded by oceanic plates) permits discussion of the relevance to mantle thermal evolution of the effect of supercontinent insulation.

2. Model Description

[5] We examine mantle thermal evolution in a plane-layer geometry model featuring seven distinct oceanic plates encircling a model supercontinent. Plate boundary positions are specified and divide the surface of the model into a tessellation of polygons characterized by piece-wise uniform velocities. The model has periodic (wrap around) side walls and an isothermal, free-slip, bottom boundary.

[6] We model mantle convection using the hybrid finite-difference spectral-method code MC3D [*Gable et al.*, 1991] to solve the equations for mass, momentum and energy conservation and use the extended Boussinesq approximation to include a depth-dependent mantle viscosity characterized by a factor of 36 increase from the upper mantle to the lower mantle.

[7] Convection is modeled with a vigor near that inferred for the Earth's mantle. Employing the viscosity at the base of the model plates, the Bénard-Rayleigh number of our calculations is 5×10^7 (additional heating results from prescribing a non-dimensional internal heating rate of 10). Calculations are performed on grids with $601 \times 601 \times 129$ nodes. Assuming a dimensional thickness of 2900 km, our $6 \times 6 \times 1$ solution domain models a lateral extent equal to the surface area of Earth's mid-mantle.

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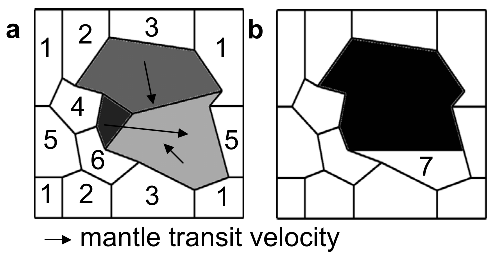

Figure 1. Model plate geometry (a) prior to, and (b) following, supercontinent formation. Arrow lengths indicate velocity magnitude and are scaled in proportion to the arrow below the plate maps, which has a length based on the magnitude of the rms velocity of the entire system at the time of supercontinent formation.

[8] Oceanic plates have isothermal surfaces and are distinguished from continental plates by their mobility and their resulting participation in the mantle circulation. Our numerical model requires that continental and oceanic plates have the same thickness. Given this restriction we choose a plate thickness comparable to the mean thickness of the thermal boundary layer (about 4.7% of the system depth). In order to simulate the first-order effect of a temperature-dependent viscosity we specify that the viscosity of the plates is 1000 times greater than that of the material immediately below. Varying degrees of insulation of the mantle underlying the continental regions can be specified by prescribing a distinct continental surface temperature gradient. Oceanic plate velocities are time-dependent and are dynamically determined using the total integrated shear stresses at the base of each plate (a force-balance calculation). This method of modeling plates and determining their velocities [*Gable et al.*, 1991] has been shown to yield plate velocities and mean heat flux values in agreement with modeling methods that utilize rheologically defined plates [*Koglin et al.*, 2005].

[9] Our initial condition was obtained by projecting a 2D solution obtained with the heating parameters and boundary conditions employed in the 3D study into the third dimension and specifying a plate geometry featuring the 9 plates shown in Figure 1a. We integrated the 3D model for several mantle overturns until a well developed 3D flow with a stable mean temperature was obtained and subsequently identified a suitable flow pattern that could be used to model the aggregation of three large continents. The arrows on the gray plates in Figure 1a indicate the instantaneous direction of the velocities of those plates at the time we simulate the formation of the model supercontinent (time 0.0 in Figures 2–4). Our model supercontinent is formed from the accretion of these three plates. Figure 1b shows the geometry of the resulting plate model, post-supercontinent-formation. The black plate is the supercontinent and covers approximately 29% of the surface area of the model (comparable to the size of Pangea) and the white plates are oceanic. The supercontinent is therefore comprised of the original top and left gray plates in Figure 1a and a portion of the bottom-right gray plate (where the remainder of the bottom-right gray plate is designated as oceanic).

[10] Below, we present results from four experiments. In Model A, we simply make the change in plate geometry indicated in Figure 1 but we do not treat the thermal or mechanical properties of the black plate any differently from the oceanic plates. In Models B-D, the supercontinent's motion ceases at the time of its formation and continental plate material can only be exchanged with the mantle if instabilities form at the base of the continental lithosphere. In each model, the supercontinents differ by their surface thermal characteristics. Model B features the same isothermal surface as the oceanic plates. The thermal boundary condition of the continent in Model C is partially insulating and features a spatially varying surface heat flux. At all locations only 25% of the heat that would conduct across an isothermal boundary is allowed to escape the continent. Given recent estimates of the ratio of the mean heat flux from oceanic regions and continental lithosphere [*Mareschal and Jaupart*, 2004] we suggest that the insulating properties of the sutured plates in Model C are most like a continent's. The thermal boundary condition of the sutured plate in Model D is perfectly insulating. Thus, the experiments presented successively investigate the effect of plate growth, plate mobility and plate thermal properties on sub-supercontinent mantle temperatures and dynamics.

3. Results

[11] Figure 2a shows an overhead view of the thermal field used as the initial condition for Models A-D. Anomalously hot material associated with both mature (notably under plate 2) and developing plumes appears under several plates. At the time of supercontinent formation a sheet of cold material can be seen plunging into the interior of the model along the boundary separating the largest gray plates. Cold down-

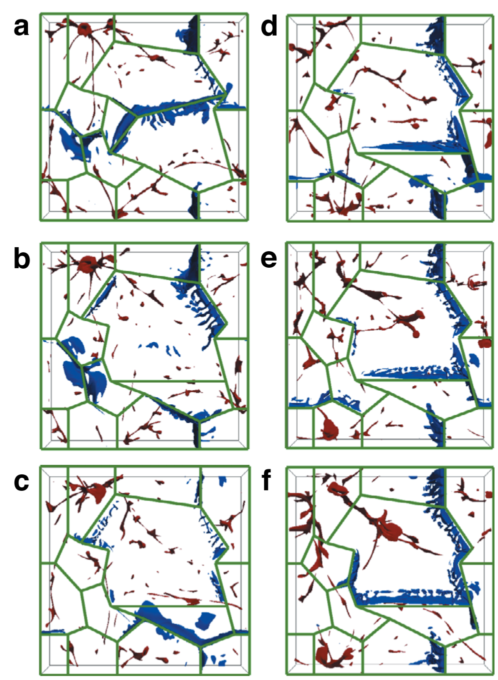

Figure 2. Snapshots of temperature isosurfaces from Model C. The top 6% and bottom 8% of the temperature fields are omitted. The red and blue surfaces have values of 0.85 and 0.5. The temperatures at the surface of the oceanic plates and the bottom of the mantle are 0.0 and 1.0, respectively. The green lines show the locations of the specified plate boundaries (see Figure 1).

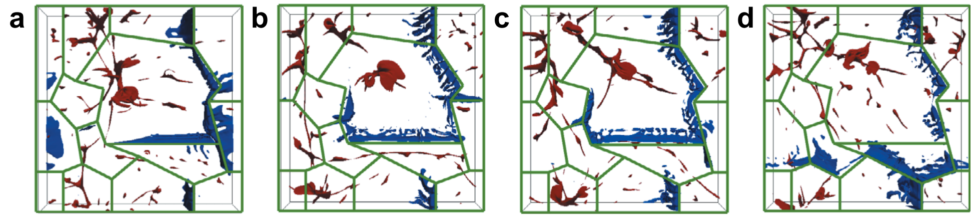

Figure 3. Snapshots of temperature isosurfaces after 5 transit times in Models (a) A, (b) B, (c) C, and (d) D. Fields are rendered as in Figure 2.

wellings are also present along the boundary separating the smaller gray plate from the larger gray plates, thus our supercontinents form over an anomalously cold region associated with downwelling mantle flow (analogous with subduction). Downwellings are also present below the convergent plate boundary separating oceanic plates 1 and 3 and the convergent plate boundary separating plate 4 from plates 5 and 6. However, in our experiments mass conservation and the fixed locations of the plate boundaries only allow for the modeling of one-sided subduction where oceanic plates collide with immobile continents.

[12] Figures 2b–2f show snapshots taken from Model C for the period following supercontinent formation. Figures 2b–2f are plotted at intervals of one mantle transit time, where the transit time is defined by the time required to travel a distance equal to the system depth at a velocity equal to the rms of the system velocity at the time corresponding to Figure 2a. We find this definition of the transit time disagrees by less than 5% with calculations of the transit time based on the temporally averaged rms value of the velocity determined over the fixed 0.006 diffusion times for which each model was integrated.

[13] Figure 2b shows that after one transit time, the downwelling associated with the boundary along which the continental fragments aggregated has dissipated and the deep mantle below the supercontinent is relatively free of notable thermal anomalies. After 3 transit times (Figure 2d) convergent plate boundaries have appeared on opposing sides of the supercontinent and after 4 transit times a large plume has appeared under the model supercontinent. This subsequently becomes the dominant plume in the calculation (Figures 2e and 2f).

[14] Figures 3a–3d compare snapshots of the temperature fields from Models A-D following 5 transit times. The ratio of the mean continental versus oceanic heat flux at these times is 0.87, 0.51 and 0.40 in Model A-C, respectively. In every case, we find that one or more large plumes appears under the black plate (cf. Figure 1b). We also found similar evolution in models that restrict continental heat flux to 15% and 50% of the value that would occur with the oceanic thermal boundary condition. We note that the large hot red patches shown in the overhead views depicted in Figures 2 and 3 are not the passive shallow features that might result from insulation but are the heads of active plumes connected to the lower thermal boundary layer by well formed conduits.

[15] The findings shown in Figure 3 suggest that the most important condition for producing one or more plumes in the region below the black plate is independent of the insulating characteristics of the overlying plate, continental or otherwise, but results instead from the cessation of the supply of cold downwelling material from above. Once the supply of cold material ceases, the growth of instabilities in the bottom thermal boundary is no longer quelled by downwelling flow [e.g., *Lowman and Jarvis*, 1996; *O'Neill et al.*, 2009] and high heat flow into the cold material pooled on the core mantle boundary instigates plume formation where downwellings are absent.

[16] In Figure 4 we present time series plots of the temperature averaged throughout both the mantle below the supercontinent (black plate) and the remaining regions of the solution domain. In Model A the mean temperature below the black plate (which has oceanic plate properties in this case) warms to the same mean temperature as the rest of the system (which cools slightly). In Model B, the mean temperature below the oceans remains warmer than that below the continental plate despite the formation of the subcontinental plume. In Model C, the influence of the continental insulation is apparent but the suboceanic regions still remain of comparable warmth to the subcontinental region. Only in Model D is there a substantial effect on sub-supercontinent temperature due to thermal insulation.

4. Discussion and Conclusions

[17] We find mantle plumes form below a large "super-plate" without the requirement of continental insulation and that the termination of subduction at the site of our simulated continental collision is sufficient to invoke the formation of plumes. Our findings suggest that continental insulation [e.g., *Anderson*, 1982, 1994; *Lenardic et al.*, 2005] is not

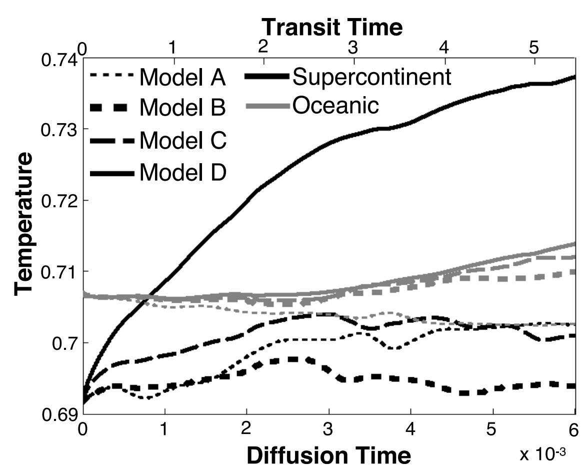

Figure 4. Volume averaged non-dimensional temperature, as a function of time, below the supercontinent (black plate) and oceanic plates in Models A-D. Averages include the temperatures within the plates.

the primary influence of supercontinents on the mantle's thermal field. Subduction shielding by a super-plate, rather than insulation by a supercontinent results in the growth of hot underlying features.

[18] The formation of active mantle upwellings below a model supercontinent has been observed in numerous past studies [e.g., *Gurnis*, 1988; *Zhong and Gurnis*, 1993; *Lowman and Jarvis*, 1996; *Yoshida et al.*, 1999; *Lowman and Gable*, 1999; *Honda et al.*, 2000; *Zhong et al.*, 2007; *O'Neill et al.*, 2009]. However, many previous studies omit the inclusion of oceanic plates. Oceanic plates inhibit the formation of instabilities in the upper thermal boundary layer and affect convective wavelength [*Lowman et al.*, 2001]. Moreover, larger oceanic plates retain more heat in a convecting system [*Monnereau and Quéré*, 2001; *Lowman et al.*, 2001]. As a result we find that average temperatures below mobile oceanic plates are comparable to the temperatures below a supercontinent (Model C). The inclusion of plates over the entire surface of our model dampens the contrast [*Coltice et al.*, 2007] between the mean temperature below the supercontinent and oceans. In comparison, heat can escape more readily from an ocean modeled by a free-slip surface condition [*Monnereau and Quéré*, 2001].

[19] Our findings are affected by the viscosity structure and Rayleigh number of our calculations. We estimate that our effective Rayleigh number is within a factor of 3 of Earth's value (e.g., based on thermal boundary layer thickness). However, a study of 2D models featuring a Rayleigh number 3 times higher than in our 3D models as well as thinner plates (60 km) suggests that as convective vigor increases continental insulation plays an even smaller role in instigating flow reversal and increasing subcontinental temperature. Moreover, in a separate 3D study, we found that the omission of mantle internal heating (and thus, in analogue with spherical shell convection, the modeling of a cooler mantle) does not change our conclusions. Other studies have suggested that an antipodal upwelling complementing an African superplume is a response to circum-Pangea subduction [e.g., *Zhong et al.*, 2007]. However, in accord with our observation that isolation from subduction enables the growth of hot mantle upwellings, we suggest an alternative interpretation, or at least an accompanying condition; namely, that a concentration of Pacific-domain plumes is a response to an overlying super-oceanic plate.

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